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Abstract

In a commonly used sense, mental workload refers to the proportion of an individual's total processing capacity taken up by a particular cognitive task or task combination. One approach to the assessment of mental workload is called the secondary task analysis. In this approach, the operator is required to carry out two simultaneous tasks, assigning one (the primary task) a high priority and the other (the secondary task) a lower priority. The primary task's mental workload is defined in terms of the degradation in secondary task performance occurring under dual- relative to single-task conditions. The validity of this approach critically hinges to the validity of the assumptions a) that human processing capacity is unitary or undifferentiated b) that the human information processing system contains no significant task-specific capacities; and c) that overall capacity remains invariant across changes in processing demand The theoretical literature pertaining to these assumptions is reviewed. It is found that while many of the theoretical issues surrounding the assumptions remain unresolved, the available data argue strongly against the general advisability of the secondary task approach The problem is that the workload ordering obtained by this approach for any set of (primary) tasks can be expected to vary with the secondary task used. Consequently, the approach will not yield a general measure of workload demand.

THE CASE AGAINST SECONDARY TASK

ANALYSES OF MENTAL WORKLOAD[1]

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I. Introduction

In its most commonly used sense, mental workload refers to the proportion of the individual's capacity-limited processing resources demanded by a cognitive task. This conception readily suggests the idea of using secondary task procecures to assess mental workload. Secondary task procecures constitute a subset of dual-task methods in which one of a pair of simultaneously performed tasks (the primary task) is assigned processing priority over the other (the secondary task). Primary task workload is defined in terms of the effect of the task pairing on secondary task performance. A highly demanding primary task, for instance, is assumed to draw heavily on the individual's processing capacity or resource pool, leaving little in reserve for the processing of the secondary task. Consequently performance on the secondary task should be quite poor relative to when performed alone. Conversely, a relatively non-demanding primary task is assumed to demand relatively little processing capacity, leaving a substantial residual for the processing of the secondary task. Performance on the secondary task should therefore be only slightly worse than when the task is performed alone. By this line of thought one is led to the more general proposition that performance decrements on a secondary task under time-sharing conditions should be proportionate to the workload demand of the primary task with which it is paired. If this proposition is correct, mental workload can be scaled by an analysis of secondary task decrement.

The assumption that secondary task performance provides a reasonable measure of mental workload or attentional demand has given rise to a substantial literature over the past 15 years. Examples of the secondary tasks

that have been examined include simple reaction time to a probe stimulus (Posner and Boies, 1971), interval production (Michon, 1966), shadowing (McLeod, 1973), paced classification (Baddeley, 1966), tracking (Baron and Levinson, 1975), memory (Broadbent and Gregory, 1965), time estimation (Brown, Simonds, and Tickner, 1967), auditory choice RT (Becker, 1976), monitoring (Berrson, Huddleston and Rolfe, 1965), mental mathematics (Huddleston and Wilson, 1971), and auditory detection (Lindsay and Norman, 1969), to name only a few. The reader is referred to Levine, Ogden and Eisner (1978) for a thorough description of the recent literature on the secondary task analyses of attention and mental workload.

One reason for the popularity of these analyses is their considerable intuitive appeal. However, as we have gained a more complete understanding of man's information-processing capacities, serious questions have been raised regarding the validity of some of the assumptions fundamental to the approach. The purpose of this report is to examine the empirical and theoretical bases of the objections that have been raised. We will show that while many of the theoretical issues remain unresolved, the empirical evidence nevertheless provides a substantial argument against the advisability of using secondary task performance to index mental workload.

To provide a theoretical framework for the arguments reviewed later in this report, we begin by summarizing the major current accounts of the nature of human information-processing capacity.

II. Models of capacity

A. Bottleneck models

The dominant models of mental capacity have been the "bottleneck" or limited capacity central processor models [e.g., Welford's (1952) single channel model, Broadbent's (1958) filter model, Treisman's (1960) filter-attenuation model, Deutsch & Deutsch's (1963) response selection model, and Keele's (1973) logogen model]. What these models have in common is the claim that our ability (or capacity) to process information is limited at some specific point (mechanism/processor, i.e., the bottleneck) in the system. Prior to the bottleneck, all information can be processed simultaneously (i.e., in parallel). Once the bottleneck is reached, however, processing must proceed in more or less serial fashion.

Bottleneck models are usually distinguished from each other by two features. One feature is the nature of the bottleneck. According to some models (e.g., Welford, 1952) the bottleneck is all-or-none; that is, information can be processed by the bottleneck only one input channel at a time (i.e., sequential processing). According to other models (e.g. Treisman, 1960), information from more than one input channel may be processed by the bottleneck under special conditions (e.g., highly salient information in a second channel). In either case, however, only a limited portion of the total possible information is processed at one time.

The second feature which distinguishes models is the location of the bottleneck. Broadbent (1958), for example, assumed that a bottleneck

occurred at or just prior to perceptual analysis, so that we can only perceive one stimulus at a time. (If two stimuli are presented simultaneously, one of them is perceived immediately, while the sensory information for the second is held in short-term store. When perceptual analysis of the first stimulus is completed--provided this does not take too long--then information regarding the second stimulus is retrieved from the sensory store and analyzed.) In the Deutsch and Deutsch (1963) model, the bottleneck occurs just prior to response selection rather than prior to perceptual analysis. According to this model, the meanings of all concurrent stimuli are extracted in parallel with no interference. The function of the bottleneck is to prevent initiation of more than one response at a time, and to select the response that is best suited to the situation. Figure 1 presents the differences between the Broadbent and Deutsch & Deutsch models.

Figure 1

Other bottleneck models may suggest other bottleneck alternatives, but the common theme is that a single limited-capacity processor or mechanism is shared by all inputs.

B. System capacity model

To some theorists (e.g., Moray, 1967), increased performance due to such factors as prolonged practice and S-R compatibility seems troublesome for the limited capacity bottleneck explanation of mental capacity. As an alternative, a "system" capacity model was suggested

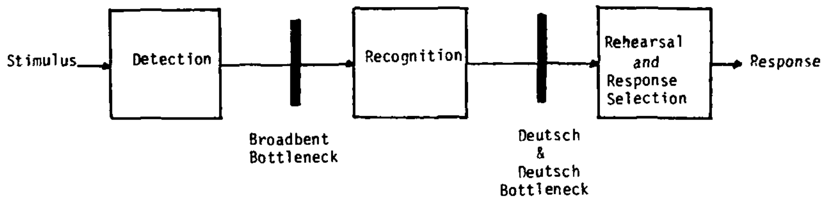

Fig. 1 Alternative conceptions of the bottleneck location (after Massaro, 1975)

in which man is assumed to possess some set quantity of undifferentiated sources that can be divided up and allocated in different ways, depending on the demands imposed on the system. Our ability to process information is limited only when total task demands exceed system limits. Parallel processing is possible where total capacity is not exceeded and where there is high S-R compatibility. Unlike the bottleneck models, then, the system capacity model has no narrow throat where parallel messages must be held up.

Moray suggests that what takes time and capacity in the central processor may not be the operation of a switch (to determine what message to attend to), but rather the transforming functions performed on input messages (e.g., parallel to serial recoding when messages come into the system in parallel but require the same output channel). Compatibility increases performance because when stimuli (S) and responses (R) are compatible, the S-R transformation imposes a minimal processing demand.

C. Multi-processor models

The ability of some individuals to perform two difficult tasks simultaneously without interference (e.g., shadowing prose while playing relatively unpracticed music on the piano) has suggested to some (e.g., Allport, Antonis, and Reynolds, 1972; Navon and Gopher, 1979; McLeod, 1978) that the human operator might best be thought of as having a number of independent and highly specialized processors (or types of resources), each with its own capacity. Instead of interference between two tasks being caused by a general purpose central processor or bottleneck,

interference would depend on the extent to which the tasks tap common processors. Parallel processing without interference would be possible if two tasks had no processors in common, or if the combined demands of the two tasks had no processors in common, or if the combined demands of the two tasks did not exceed the capacity limits of any shared processors. When combined task demands do exceed the capacity limits of one or more shared processors, the system would either exhibit single-channel characteristics or both tasks would suffer some decrement. Consider the following figures:

Figures 2 & 3

In Figure 3, processor D is shared by two streams of input, S1 and S2. If the capacity of D is overloaded by the demands of S1 and S2 combined, then interference will result. In Figure 4, on the other hand, S1 and S2 share no processors, and consequently no interference is obtained. The key point is that in the multi-processor model interference depends on the combination of task demands, and thus is not mandatory.

D. Combination models

In an effort to accommodate apparently conflicting evidence, some recent models of mental capacity combine features from more than one of the previously described models, as well as adding new features. Three such models will be described.

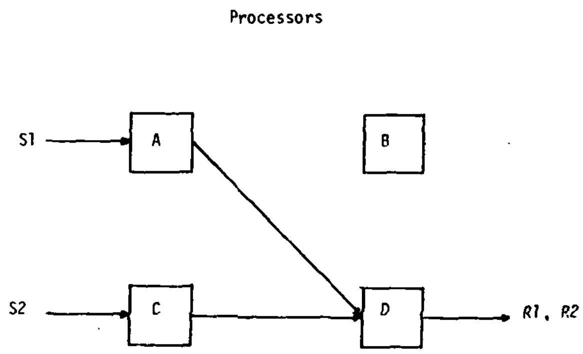

Fig. 2. Case of shared processor. (Interference occurs if processor D is overloaded.)

Processors

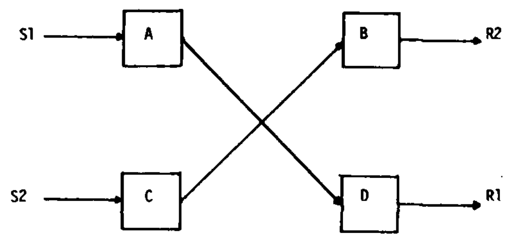

Figure 3. Case of no common processor. (no interference)

Kahneman (1973) asserts that neither a structural model nor a capacity model is adequate alone. Both structural interference (i.e., the specific interference that occurs when the same mechanism is required to carry out two incompatible operations at the same time) and capacity interference (i.e., the non-specific interference that occurs when the demands of two activities exceed available capacity) occur. In addition, Kahneman proposes that effort or attention is controlled by task demands; that is, tasks at different levels of complexity elicit different degrees of arousal and different amounts of attention (independent of the performer's intentions). This implies, as Figure 4 illustrates, that total capacity is not constant for all tasks. For simple tasks, total capacity available for processing is less than the total capacity available for difficult tasks.

Figure 4

Nonspecific interference between tasks is due to an insufficient response of the system to current demands, and to narrowing of attention when effort is high. Because available capacity depends on the complexity of tasks, interference can occur even when the total load on the system is far below total capacity. The amount of interference, however, is an increasing function of load. At low levels of load, there may be little or no interference between tasks, but as overload is approached the gap between demand and supply increases.

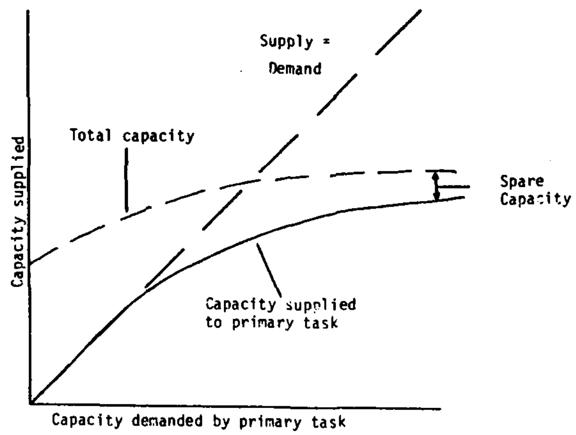

Fig. 4. Supply of effort as a function of demands of a primary task. (from Kahneman, 1973).

Kahneman's model goes far in integrating many of the ideas presented in the preceding models, but as the next models show, other combination views are possible.

Like the Deutsch and Deutsch (1963) model described earlier, the logogen model of Keele (1973) maintains that information enters sensory organs and proceeds to activate memory information in parallel and without interference. The limitation in the system arises in coordinating information available from the environment with information regarding goals so as to determine what action should be initiated. Thus, a selector mechanism (corresponding to what we call attention) prior to final action is thought to be a major source of limitation. This model is illustrated below:

Figure 5

Elaborating on this model, Keele and Neill (1978) point out that in many situations parallel access to memory entails cost. For example, complex stimuli in the same modality may mask or merge with one another, or codes from irrelevant messages may conflict with relevant message codes. Evidence that we might filter information prior to memory or preset the system to select some inputs at the expense of others (Posner and Snyder, 1975) has suggested to Keele and Neill that attention might be better viewed as a control process that can influence the flow of information rather than as some limited capacity always invested at a particular place in processing. They point out that as an active control process,

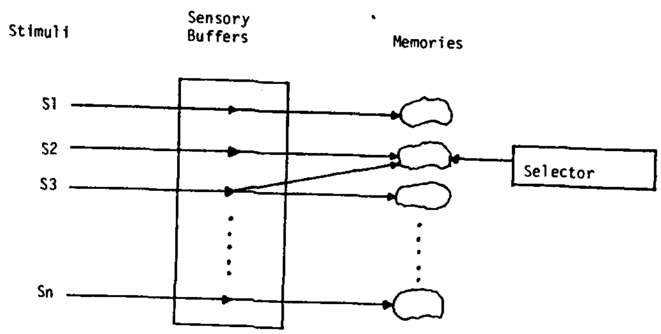

Figure 5. Keele logogen model (from Keele & Neill, 1978)

attention may function in several ways. It can modulate the flow of information to memory, thereby attenuating an input. At other times, the control process can allow entry to all codes, but then select only a subset of these codes for further processing. Finally, the control process can preset itself for expected information, thereby improving overall efficiency.

What does attention as a control process say about mental capacity and the interference between tasks? Among other implications, it seems that the limit on processing might depend on how well the control process is able to regulate and coordinate the flow of information relevant to the tasks being attempted. If regulation and coordination are easy, little task interference will occur. If, however, regulation and coordination of task information is difficult or impossible, interference will be substantial or complete, respectively.

Posner and Snyder (1975) also see attention as an active component in information processing. They identify attention with a brain mechanism of limited capacity which can be directed toward different types of activity. Attention, for example, may be directed toward a particular input channel, a particular response, a particular structure in the memory system or a particular pathway within an input or other processing structure. When attention is directed to one of these structures or pathways, information located within it is given priority in accessing capacity-limited resources such as reponse mechanisms or decision processes. Thus the processing of signals using the attended structure or pathway will be carried out more rapidly. Along with this facilitation or

benefit, however, there is a cost. Since attention has a limited capacity, our ability to process other signals that do not use the structure or pathway given our attention is inhibited (unless processing is automatic).

From this description, one can see that our ability to consciously process information (i.e., our capacity) will be limited by the type of activity the attentional mechanism is involved in, and within the particular activity, by the particular pathway that is given priority. This suggests that our ability to perform two tasks simultaneously may depend on where attention is directed and how much switching this mechanism must carry out to enable the two tasks to be performed.

III. How different are the models of human capacity?

The combination models demonstrate how features from different models can be brought together without conflict. Kahneman's model, for example, incorporates both structural interference (a multi-processor feature) and capacity interference (a system capacity feature). Both of the "active" attention models (Keele and Neill, 1978; Posner and Snyder, 1978) incorporate bottleneck notions (e.g., a limited-capacity central processor or mechanism) and system capacity notions (flexible allocation of resources). If such features are not incompatible, one may wonder just how distinct the non-combination models are. Could they, perhaps, be complementary views of the same phenomenon? And would this explain why the combination models can account for more data than the non-combination models?

A closer look at the bottleneck, system capacity, and multi-processor models reveals that there is considerable overlap among the models. In the

discussion that follows, this overlap will be examined in the hope of gaining a better view of the general features of mental capacity. We will begin with a consideration of the similarities between bottleneck and multi-processor models.

A. Comparison of bottleneck and multi-processor models

To explain why some stimuli are easily analyzed simultaneously and some are not, Treisman (1969) maintains that it is plausible to assume that the perceptual system consists of a number of relatively independent subsystems or analysers which code different aspects or dimensions of incoming stimuli (e.g., color, orientation, pitch). Treisman goes on to say that parallel processing is possible if different stimuli require separate analyzing systems, but serial processing takes place if two stimuli share an analyzer. (As the reader has probably already realized, this explanation is almost identical to the multi-processor model, yet Treisman is usually thought to hold a bottleneck view.)

It has shown that some individuals can perform two difficult tasks simultaneously and without interference (Allport, In Press). Multi-processor models can easily handle such occurrences by claiming that the two tasks do not tap common processors (or do not overload any common processors) and, therefore, do not interfere with each other. Bottleneck models, on the other hand, have trouble with the above finding. To deal with these problematic results, bottleneck models must assert that one or both of the concurrent tasks must be automated. But what is this notion of automation? LaBerge (1975) suggests that attention may be

gradually withdrawn as we overlearn a task. If attention is thought to be the bottleneck in performance, then it might be said that as attention is withdrawn, the tasks involved no longer share common processors. This brings us back to the multi-processor view.

Looking at this issue from the opposite perspective, consider the pairing of two highly practiced and highly different tasks. Initially, at least, pairing such tasks will result in performance decrements for one or both tasks. Bottleneck models have little trouble explaining such results since both tasks must encounter a shared processor (namely the bottleneck) at some point. But, if the tasks are highly different, how would multi-processor models explain such results? They could claim that the two tasks really do share some "unapparent" processor. But suppose, as often happens, with more practice the tasks can be performed at their single task levels. What happens to the "unapparent" processor?

What has been suggested (Allport, In Press) is that there may be some specialized resources that are devoted to emergency or uncertain situations--such as combining two previously unpaired tasks. These resources would be shared by the two tasks (resulting in interference) until paired performance became more certain and/or emergencies no longer occurred. These "specialized resources" for emergency situations sound suspiciously like what bottleneck models call attention.

Finally, it should be noted that although bottleneck models usually emphasize a specific limited-capacity central mechanism, they do not rule out the possibility of other limited-capacity sub-structures that may be necessary for some, but not all, tasks. These limited-capacity sub-structures

would correspond to other processors in the multi-processor models that are not needed for all tasks.

At this point, it may be clear that if the bottleneck in a bottleneck model was considered to be one of several capacity-limited mechanisms, and if there were instances where this bottleneck could be by-passed (as automation suggests), then there would be very little to distinguish bottleneck and multi-processor models.

B. Comparison of system capacity and multi-processor models

At first glance, it might seem that structural interference would have no meaning for a system capacity model with undifferentiated resources. At second glance, however, structural interference, or its functional equivalent, is very relevant to a system capacity model. An idea stressed by Moray (1967) is that "it is the functions performed on the (incoming) messages themselves that take up capacity" (p. 87). It follows that if several messages are coming from a single modality or structure (or going to a single structure), more mapping functions, and hence more capacity, will be needed to keep the messages distinguishable. If, on the other hand, structures do not overlap, fewer functions will need to be performed on messages, and the system will be able to devote more capacity to performance. These predictions are quite compatible with multi-processor views.

As we mentioned previously, some multi-processor models suggest that in some situations special resources can be called upon when tasks encounter emergencies or uncertainties. According to Allport (In Press),

these resources are not preallocated to either task but may be used by either task when needed--even though the tasks may entail no structural competition for specific resources. The notion of resources being applied where needed by structurally different tasks is very compatible with Moray's idea of undifferentiated system capacity.

C. Comparison of bottleneck and system capacity models

The least amount of overlap appears between bottleneck and system capacity models. This should not be surprising when it is realized that the system capacity models arose as a counterproposal to the bottleneck conception. Even so, overlap is not completely absent. Moray (1967) conceded that although capacity can be allocated in different ways in a system capacity model, "there may be some functions which are permanently built into the hardware and can never be switched out," (p. 87). This suggests that the general pool of resources or capacity (like the resources in bottleneck models) may not be entirely free of constraints.

D. Theories of processing capacity: conclusions

Several generalizations regarding mental capacity emerge from the foregoing comparisons.

First, there is obviously some limit to our mental capacity. The impetus behind all of the models described is the fact that we are continually confronted with situations in which we cannot process and/or act upon all the information available to us. However, because of such factors as

compatibility, practice strategies, and automaticity, our limited-capacity is not easily translatable into performance limits.

Second, when two tasks are performed simultaneously, interference may or may not occur. When the two tasks do interfere, all models would agree that some capacity has been exceeded. Bottleneck and multi-processor models, for example, would agree that at least one processor (or special resource) is shared by the two tasks. However, neither of these models rules out the possibility of more than one processor being shared. Furthermore, all models allow the possibility of structural interference at some stage. This latter interference, of course, would depend on the particular tasks being performed. In short, then, interference may occur for a number of reasons.

When two tasks do not interfere, all models would agree that mental capacity has not been exceeded, and that there is no structural interference. Bottleneck and multi-processor models would agree that no processor is being overloaded. However, there is the possibility that overload did not occur because one or both tasks became automated. In addition, one model (Kahneman's) suggests the possibility that total capacity may have increased to prevent interference. In short, there are several reasons why interference might not occur.

Third, most contemporary models include provision for a processing component (usually called attention) which is required at least under unfamiliar or unpredictable conditions. This component does not seem to be tied to any particular processing stage or task. Instead, it can be deployed to different stages and in different ways to regulate and coordinate information

processing according to task demands. Interference (or facilitation) between tasks seems to depend on how this flexible component is used; and different results may occur with different uses. Finally, as performance becomes highly practiced, the role of this component seems to diminish.

IV. Research on the nature of human processing limitations

Among the assumptions represented in the foregoing accounts, two seem especially crucial to the secondary task approach to workload assessment; first that the human processing capacity or resource pool is unitary, and second that this capacity remains fixed across levels of processing demand. We will treat these in turn.

A) Unitary processing capacity.

The central assumption of the secondary task approach is that all demanding cognitive tasks, by definition, tap a single central capacity or resource store (Welford, 1952; Broadbent, 1958). It is this capacity that is presumably partitioned between primary and secondary tasks. Given the alternative view, in which information processing is carried out by task-specific structures or resource stores (McLeod, 1977; Navon and Gopher, 1979), no generalized workload measurement could be possible. The problem posed by the multiprocessor view is that the workload measurement obtained for any given (primary) task is wholly dependent upon which and how many specialized processing structures it shares with the concurrently performed secondary task. Under such circumstances, it is

apparent that the workload ranking of any even modestly diverse set of primary tasks will vary across differing secondary tasks, and mental workload as a general property of cognitive tasks would become meaningless.

This problem is not eliminated in accounts which assume a central processing capacity in addition to specialized (e.g. task-, code-, modality-, or stage-specific) subcapacities (Kahneman, 1973; Keele & Neill, 1978). Here, as in the case of strict multiprocessor models, assessed workload will be affected by the number and types of substructures commonly utilized by the primary and the secondary tasks.

B. Is capacity unitary?

Evidence contrary to the assumption of a unitary processing capacity comes from three general sources. The first of these consists of studies demonstrating the occurrence of "structural interference" (Treisman and Davies, 1973) in human information processing. The second consists of studies demonstrating that processing capacity, as indexed by time-sharing performance, seems uncorrelated across task combinations. The third consists of studies demonstrating time-sharing without apparent interference. The first of these two sources of evidence points to the existence of multiple capacities. The second and third have been used to argue against a multi-purpose central processing capacity and exclusively in favor of task-specific subcapacities.

1. Structural interference. Structural interference is a term used in reference to the fact that concurrent tasks exhibiting similar properties

will under certain conditions yield greater mutual interference than will dissimilar tasks. The implication of such findings is that similar tasks compete for the use of, and under certain conditions can overload, common processing structures.

Consequently, evidence for structural interference provides support for the idea of multiple capacities or processing channels.

a. Structural interference during stimulus input

The generally accepted criterion for asserting the presence of structural interference at input is the demonstration that, all else equal, time-sharing performance is poorer when two tasks share an input modality (e.g., both visual) than when not, and is poorer when similar stimuli are presented within a modality relative to when dissimilar stimuli are presented within that modality. A problem immediately arises concerning the relation of structural interference to the well established phenomenon of masking. Structural interference is presumed to take place under conditions imposing an informational overload on specific processing structures. However, masking refers to a reduction in stimulus quality that can occur when the so-called masking stimulus appears in close temporal and spatial contiguity to a source of information that is already marginal in terms of its duration and/or intensity (the critical stimulus). The reductions in stimulus quality produced by the masking stimulus are usually interpreted in terms such as 1) interruption, in which the masking stimulus leads to a termination of (or inhibition of) critical stimulus processing; or 2) integration, in which information from masking and critical stimuli overlay such that their unique elements are

difficult to discern (see e.g., Turvey, 1973; Breitmeyer and Ganz, 1978). While both interruption and integration in a sense represent types of structural interference, the locus of the interference is relatively peripheral, is usually contingent upon spatial overlap (masking) or at least close temporal contiguity of the mask and the critical stimulus (metacontrast), and entails interactions between the processes generated by the two stimuli. As we intend the terms here, structural interference refers to a process that is probably more central than that involved in masking, is not contingent in close spatial contiguity between stimuli, and does not appear to be contingent upon interactions between stimulus processes.

If we disregard masking as an instance, the evidence for structural interference during input is suggestive but not conclusive· much of the data that have been cited as evidence for such interference are subject to alternative interpretations. As we will see, however, in most instances the alternative accounts pose as much of a difficulty for the secondary task approach to workload measurement as does the structural interference interpretation.

One early piece of evidence hinting at the occurrence of structural interference during input is the finding by Lappin (1967) that we can more accurately report the different attributes of one object (e.g., its color, form and size) than one attribute of three objects (e.g., red, green and blue or square, circle and triangle). According to the structural interference notion, these data reveal that a common structure must be used for the processing of color (or form) information, and this structure became overloaded in the second condition of the Lappin experiment. An alternative interpretation

(Kahneman, 1973) is simply that attention is addressed more efficiently to objects than to dimensions.

In a study frequently cited in support of the existence of structural interference during input, Allport (1971) required subjects to report the identity either of simultaneously presented geometric objects and numerals imbedded within them, or of the objects and the color of the ink in which they were printed. Performance was found to be worse in the former instance, suggesting (as in the Lappin [1967] experiment) that a common capacity-limited processing structure concerned with the analysis of form is required in the identification of figures and numerals. At first glance, these results seem subject to a metacontrast interpretation since figures and numerals were in close spatial contiguity, were presented relatively briefly (20 milliseconds), and were followed by a masking stimulus which served to further reduce overall stimulus quality. However, any simple metacontrast interpretation would seem to be eliminated by the fact that the performance on the form-form condition was worse than that on the color-form condition only for the second of the stimulus dimensions reported on a trial. That is, when it had to be reported first, neither the numeral nor the figure was worse under the numeral-figure than under the numeral-color or figure-color condition. This means that the initial perception of the first dimension interrogated was not affected by the combination of dimensions involved, as would be implied by the metacontrast interpretation. Allport interprets this finding as showing that the two form dimensions had to be processed in serial fashion through a limited capacity form analyzer, and that information regarding the second of the two form dimensions to be reported in each trial had to be

delayed to some extent before its processing could be completed. This analysis is, of course, quite compatible with the idea of structural interference.

The Allport results are subject to an alternative interpretation, however. It could be that the pattern mask used in this study more effectively disrupted processing of the two form dimensions than it did the color dimension. Consequently, the task of reporting the color and then one of the form dimensions may have been easier than that of reporting the two form dimensions.

A different problem exists in connection with a subsequent study by Allport (Allport, Antonis and Reynolds, 1972). In this study, it was shown that subjects are able to shadow continuous speech (prose passages) while they are simultaneously encoding complex visual scenes for later recognition or sight reading piano music. In the latter case, sight reading was about as good under "divided attention" conditions as when carried out alone. The authors draw a contrast between these results and those obtained under dichotic listening conditions (independent messages simultaneously input to the two ears), where recognition and memory performance for information input through an unattended channel is usually quite poor (Moray, 1956; Norman, 1969). Two implications have been drawn from this research: 1) the poorer performance usually observed under dichotic listening conditions implies the presence of structural interference within the auditory modality; and 2) the lack of substantial interference under conditions of the Allport et. al. study implies the absence of a general all-purpose central capacity. Alternatively, one could interpret the relatively poor performance obtained in dichotic listening as due to masking and/or the relatively high attentional (capacity) demands of

the recognition tasks subjects have been required to carry out concurrently with shadowing in dichotic listening studies. The failure to find substantial interference between either picture encoding or piano sight reading and shadowing is also open to alternative interpretation. In the case of picture encoding, Shaeffer and Shiffrin (1972), and Hintzman and Rogers (1973), have shown that the opportunity for rehearsal has little or no affect on recognition performance for pictures. The processing demands of picture recognition tasks thus appear to be quite minimal since initial registration. Similarly, piano sight reading for relatively experienced pianists may also be a highly automated task, requiring little processing capacity. Given that neither picture retention nor piano sight reading clearly imposed significant processing demands under the conditions of the Allport, et al. (1972) study, the results reported remain equivocal in relation to the issue of unitary versus multiple capacities.

Somewhat less equivocal are the results of two studies reported by Treisman and Davies (1973). In the first study, subjects were presented with three pairs of simultaneous messages, both visual, both auditory, or one visual and one auditory. The stimuli were either both words, both non-verbal, or one a word and one non-verbal. The task was to report the items presented from the left, then those presented on the right. Two findings are of interest. First, performance was generally better when one stimulus was visual and one auditory, relative to when both were visual or auditory. Second, in the case of auditory stimuli, performance was poorer when both stimuli were words or both non-verbal (tones) relative to when one was a word and the other was non-verbal. The first of these two findings is

particularly impressive in the case of paired visual stimuli since the stimuli were presented with sufficient duration and spatial separation to preclude a masking factor. This was not true with auditory stimuli, and indeed, the similarity effect (the second finding above) could reflect the fact that similar items (word-word or tone-tone) are more effective mutual maskers than are dissimilar ones (word-tone).

In the second study by Treisman and Davies, subjects were presented on each trial with 8 word pairs in rapid succession. A pair appeared simultaneously, both visual, both auditory or one visual and one auditory. To equate auditory and visual items in difficulty, the latter were degraded by bracketing them with X's (e.g. XDOGX) and superimposing a thin mask. The task was to detect a target item located at some point within each list. Under one condition, targets consisted of words containing an "END" component (as in PRETEND or TENDER). Under another condition, targets were defined as animal names. The data revealed that both physically ("END" detection) and semantically (animal names) oriented recognition performance (probability of correct detection) was superior under visual-auditory conditions. Control conditions, where subjects were instructed prior to each trial to focus attention on only one input channel, were used as a control for masking effects. Where some masking was observed under auditory-auditory conditions, its magnitude was insufficient to account for the modality effects obtained under divided attention conditions. Considered together, the two experiments reported by Treisman and Davies seem to provide reasonably good support for the existence of structural interference during input. Keele (Personal Communication) has recently replicated and extended the second of the two

Treisman and Davies studies. Subjects in the Keele study were simultaneously presented with two items, both visual or one visual and one auditory. The task was to respond if the pair presented on a trial contained a digit, but not otherwise. Three different forms of visual stimuli were presented: 1) visual stimuli were either digits (e.g. 2) or letters (e.g. T); 2) spelled out digits (TWO) or words (TEA); or 3) spelled out digits or words bracketed with Xs (XTWOX or XTEAX), as were used in the earlier Theisman and Davies study. When stimuli were both visual, the items appeared one above the other $\binom{\text{TEA}}{\text{TWO}}$. One purpose of the Keele design was to determine whether the structural interference effects reported by Treisman and Davies could be obtained with less complex stimulus forms. In support of the analysis of Theisman and Davies, structural interference was obtained with bracketed and to a lesser extent with unbracketed words, i.e., visual-visual presentation. However with digit-letter stimuli, so-called structural "facilitation" rather than structural interference was obtained. That is, performance was better under visual-visual than under visual-auditory presentation. The overall pattern of results obtained by Keele seems compatible neither with unitary nor multiple capacity accounts in any strict sense. The structural interference observed under the two most demanding stimulus conditions provides support for the idea of multiple capacities. However the structural facilitation observed under the least demanding condition seems more compatible with the idea of a unitary capacity which must be switched between input channels. In this respect the data suggest that the greater the distance traversed when switching from one input channel to the other, the longer (and thus more costly) the switching time. These data are perhaps most consistent

with an account suggested by Posner (Personal Communication) in which central capacity is likened to a targetable spotlight that must operate within the capacity limitations of the specific processing structures toward which it can be oriented. Whether one gets structural interference or structural facilitation depends upon whether the input is sufficient to overload specific processing structures (as in the two most difficult conditions of the Keele experiment).

While the preceding studies suggest that structural interference can occur during input, the results of two more recent studies suggest otherwise. In one of these (Hawkins, Olbrich-Rodriguez, Hallaron, Ketchum, Bachmann and Reicher, 1979), subjects performed a double stimulation (or PRP) task in which stimuli for both primary and secondary tasks were visual or the primary stimulus was auditory and the secondary stimulus was visual. Interference effects, defined in terms of secondary task performance, were virtually identical under visual-visual and auditory-visual conditions. While this result would seem to argue against structural interference, a closer examination of the demands of the double stimulation procedure suggests any strong conclusion is probably unwarranted. The problem is that subjects are instructed in the double-stimulation task to respond to the second task only after they have responded to the first. This instruction may introduce "dead time" into Task 2 processing in the sense that action on this stimulus is delayed until Task 1 processing has been completed. Differences in stimulus processing time produced by structural interference on visual-visual trials could be absorbed during this dead time, and consequently not appear in overall reaction time. Note also that the results of this

study are inconsistent with the implication of some unitary capacity models that visual-visual conditions should show less interference than auditory-visual (structural facilitation). However, this data relation may also have been obscured by the introduction of "dead time" into Task 1 processing. Consequently the double stimulation paradigm probably should not be viewed as analytic regarding the question of structural factors in input processing.

Other evidence seemingly at variance with the idea of structural interference during input appears in a probe RT study reported by Proctor and Proctor (1979). The primary task was delayed physical letter-matching (Posner and Mitchell, 1967). A probe (either a tone or a light) was presented at varying points in time prior to presentation of the first of the two stimuli to be matched, between the two stimuli or after presentation of the second. The task was to quickly respond upon detecting the presence of the probe. Since the primary task was visual, it seems reasonable to expect that if structural interference were operative during input in this task, probe RT would show greater disruption in the case of the visual relative to auditory probe. This was not the case, however, unless the probe modality was uncertain, and then only in modest degree. When subjects knew in which modality the probe would appear, no difference in probe interference was obtained. The major problem with these data as an argument against structural interference during input is the fact that Posner and Boies (1971) have shown that stimulus encoding in the delayed matching task requires little or no processing capacity. Thus there is no reason to expect that the kind of overload necessary to produce structural interference was generated in the Proctor and Proctor task.

In summary, we have reviewed a number of studies that are pertinent to the issue of whether structural interference occurs during the input phase of information processing. While much of the data seem ambiguous and at times contradictory, the weight of the evidence points to the presence of structural interference during input, at least under conditions of high stimulus complexity.

b. Structural interference during output

Output structural interference is indexed by the finding that dual task performance is worse when the tasks use a common output modality relative to when different modalities are used. Excluded from consideration are situations in which the same peripheral motor elements are required by both tasks. For example, it is apparent that we cannot utter two distinct vocal responses at once, or press two spatially separated keys with the same finger. The problem in both these cases stems from a structural limitation, but this limitation is largely a matter of motoric incompatibility (a muscle system cannot commit two structurally incompatible acts at once). Our interest is in dual-task situations that overload more central motor processing structures such as those involved in motor programming or response initiation. Evidence for overload of this type is sought in dual-task situations, for example, in which one task requires a left-hand key response and the other task requires either a vocal response or a right-hand key response. Under these conditions, output structural interference would be implicated by the finding that the bimanual task pairing produces poorer performance than the vocal-manual pairing.

The number of studies in which the existence of output interference has been assessed is rather small. The results, however, are quite consistent in demonstrating the presence of response modality effects. Whether or not these effects reflect structural interference is not always clear, however.

McLeod (1978) assessed the role of output interference in the probe RT paradigm (Posner and Boies, 1971) by comparing the extent and pattern of probe interference under two conditions, one in which the primary (delayed letter matching) and probe task both required manual responses (bimanual condition) and one in which the primary task required a manual response and the probe, a vocal response. The magnitude of probe interference was substantially larger in the bimanual case, indicating that subjects have greater difficulty simultaneously programming and/or initiating two manual responses than a verbal and a manual response.

In an earlier experiment, McLeod (1977) tested subjects in a dual-task format in which one task was (right-hand) manual output tracking and the other was a two-tone identification requiring either a vocal or a left-hand manual response. The tracking task was performed significantly worse when time-shared with the manual identification task. Again, the data suggest that left and right hand manual responses are produced by a single limited capacity process, whereas manual and vocal responses are produced by separate processes.

A conclusion similar to that of McLeod was reached by Hawkins, Rodriguez and Reicher (1979) based on the results of a double-stimulation study involving either bimanual or vocal-manual responses. The primary task was

two-choice discrimination, requiring a left-hand key press response. The secondary task was also two-choice discrimination, (using stimuli that differed from those of the primary task), requiring either a right-hand manual response or a vocal response. Substantially greater interference in secondary task performance occurred under bimanual conditions.

It should be pointed out that both the McLeod (1977; 1978) and the Hawkins, et. al. (1979) results are subject to an alternative interpretation. It is possible that stimuli in the dual (or probe RT, or double stimulation) task situation affect processing much in the same way as do color Stroop stimuli. In the Stroop task subjects are shown color words, e.g. RED printed in colored ink, e.g. green. The subject is instructed to report the ink color, ignoring the color word. This is quite difficult for most subjects to do. The problem is viewed as at least partially a result of response competition. Both the name of the color word and the name of the ink color are activated on each trial, and the subject must engage in a time-consuming process of determining which of these activated memory codes is appropriate, i.e., was generated by the ink color. Similarly, in the McLeod and the Hawkins et al. studies, it is feasible that on occasions where subjects process both stimuli (primary and secondary) to the point of response retrieval, the problem remains of determining which manual response is required by each stimulus. The problem of matching up stimulus representations with their appropriate response should be reduced when the stimuli have been paired with highly discriminable output channels. An interpretation of this sort is perfectly compatible with the idea of a unitary general-purpose processing capacity. Nevertheless, regardless of whether one interprets the

data we have described in this section in terms of structural interference or similarity-dependent response competition, the data still pose a serious problem for attempts to use secondary task methodology in assessing mental workload: in either case, the workload measurement obtained for any primary task could be contingent upon the output modality of the secondary task.

c. Central structural interference

Central structural interference is implied by the finding that dual or secondary task performance is adversely affected when the central processing demands of the two tasks are made more similar. By central processing demands, we are referring to coding systems (e.g., visual or phonetic) and operations (e.g., specific transformations) that must be imposed on input in order to carry out a task. Moreover, within particular coding systems, similarity of content (i.e., in the identity of the internal representations on which operations are imposed) should also promote structural overload. An additional problem arises, however, when the content of two simultaneous tasks is not clearly distinguishable on a formal or semantic basis in that confusions may occur regarding the assignment of content to tasks. Examples are abundant in the memory literature. The Stroop effect is another instance. While confusions of this sort should probably not be viewed as manifestations of structural interference, they nevertheless pose a difficulty for the secondary task analysis of mental workload. That is, if primary and secondary tasks are similar in content, the confusability factor will produce an inflated (non-general) estimate of primary task workload.

An early demonstration of central structural interference effects appears in the results of an important study by Brooks (1969). Subjects

heard a sequence of digits which they were to imagine in a particular spatial arrangement within a 4 x 4 matrix. For instance, they might hear, "A 3 is located in the upper right corner . . . a 7 is immediately below the 3 . . . a 5 is directly to the right of the 7," etc. Following an interpolated task with either auditory or visual stimuli, subjects were required to reproduce the digits in their correct spatial arrangement. Brooks found that recall was poorer when the interpolated task used visual stimuli, implying that maintenance of the spatial arrangement of the digits and the visual interpolation required the use of a common, capacity-limited representational system.

Baddeley, Grant, Wight and Thompson (1975) studied the effect on visual pursuit tracking of two types of primary task. In one of these tasks (visual) the subject was shown a block capitol letter with an asterisk at one corner. The letter was removed and the subject was required to classify the successive corners of the figure according to whether or not they come from the top or bottom of the figure. In the other primary task (verbal), a sentence was presented and the subject was required to categorize each successive word according to whether or not it was a noun. The verbal primary task had no effect on the secondary tracking task whereas the visual primary task did. We see once again that tasks imposing demands on a common representational system are more difficult to time-share than those tapping different systems.

North (1977) tested subjects on all pairwise combinations of four tasks, including each task paired with itself. The tasks included tracking, immediate digit identification, digit classification, and delayed digit identification. Performance on both tracking and immediate digit identification was affected

more by concurrent tasks that were similar than those that were dissimilar. That is, when paired with another tracking task, tracking was poorer than under any of the conditions using digit stimuli. When paired with another task using digits as stimuli, performance on the immediate digit identification task was inferior to when it was paired with tracking. However, it should be noted that these results may be due to the response competition factor discussed earlier in connection with the McLeod (1978) study.

Along similar lines, Sverko (1977) tested subjects on all pairwise combinations of four tasks, including digit cancellation, auditory discrimination, pursuit rotor and mental arithmetic. In all cases, performance on a task under dual-task conditions was damaged more when the task was paired with itself than when paired with a different task.

d. Structural interference: Conclusions

In the foregoing sections we have reviewed a number of studies that have been cited as demonstrating structural interference at one point or another along the information processing sequence. Many of the studies we have cited are subject to alternative interpretations. However, the weight of the evidence tends toward the conclusion that structural interference can occur at a variety of points during the information processing sequence. Regardless os whether structural interference exists, however, the data we have reviewed are consistent in demonstrating that the similarity of the input, output, and central processing demands imposed by two concurrent tasks will have an impact on the extent of the interference produced. This fact is devastating to the secondary task approach to workload measurement for it means that a generalizable measure of mental workload cannot be obtained.

2. <u>The failure to find a general time-sharing ability</u>

If there exists a general purpose (undifferentiated) capacity which all <u>demanding</u> information-processing tasks take part in, one would expect to find that the measured capacity to carry out combinations of such tasks is correlated: a person with high capacity who is good at time-sharing one pair of tasks ought to be good at time-sharing another pair, regardless of the similarity of the two task pairings.

The earliest reported effort to investigate this issue was published over 60 years ago by McQueen (1917). McQueen tested 35 twelve-year-olds on eight different tasks, presented singly and in four pairwise arrangements. Examples of the tasks used were counting by three's and letter cancellation. A correlational analysis revealed no evidence for a general time-sharing ability: performance on one task pairing failed to predict performance on another pairing when the two pairings were comprised of dissimilar tasks.

Sverko (1977) tested 60 subjects on four information-processing tasks presented both singly and in all possible pairwise combinations. Included among the tasks were visual choice RT, rotary pursuit, mental arithmetic, and auditory discrimination. Two different analyses were used in an effort to detect a general time-sharing ability. First, the performance of subjects on each task under each condition (including both single and dual task conditions) was correlated with that on each task under all conditions. The resulting intercorrelation matrix was then subject to a principle component analysis. If a general time-sharing factor was manifested in the data, five factors should have emerged, four task-specific factors and a general time-sharing factor. In fact, only four factors could be extracted, and these were clearly task-specific. Second, a total performance decrement score was

calculated for each task pairing. This score is simply the sum of the proportionate loss on the two tasks when paired, relative to when they are carried out singly. The performance decrement score for each task pairing was then correlated with that for each other task pairing with the constraint that no common tasks appeared across pairings. The obtained correlation was essentially zero in all cases, again suggesting the absence of a general ability factor.

The third study was by Jennings and Chiles (1977) whose results have been interpreted (Damos, 1977) as favoring the existence of a general time-sharing ability. A close examination of the Jennings and Chiles results, however, indicates that while they may have identified a time-sharing factor, this factor is not general across the tasks they studied. Rather, what they have uncovered appears to be a task-specific subability. Their procedure, like that of Sverko, was to factor-analyze the results of a set of tasks when these were carried out singly and in combination. One of the factors extracted from the analysis showed high loadings for two different low-signal density, visual monitoring tasks, but not when they were carried out singly. However, because no other tasks, including two-dimensional tracking, loaded on this factor under concurrent conditions, the factor is clearly quite specific to a particular class of monitoring tasks.

Recent work carried out at Oregon (Hawkins, Rodriguez and Reicher, 1979a; Hawkins, Olbrich-Rodriguez, Halloran, Ketchum, Bachmann and Reicher, 1979b) provides even stronger evidence against the idea of a general time-sharing factor. The time-sharing performance of 16 undergraduates (Hawkins et al., 1979a) and of 12 pilot trainees and 12 undergraduate non-pilots was evaluated under eight dual-task conditions (Hawkins, et al., 1979b). Three task

characteristics--input modality (auditory or visual), output modality (vocal or manual), and task type (information conservation versus information condensation) were systematically manipulated across conditions in an effort to vary the nature of the specific time-sharing demands imposed. To assess their generality, indices of time-sharing (dual-task decrement scores) were correlated across task pairings. An index was viewed as reflecting a general ability if it correlated across pairings imposing dissimilar time-sharing demands. By this criterion, our analysis revealed no evidence whatsoever for a general (transsituational) time-sharing factor.

Results similar to those of the two Hawkins, et al. (1979a; 1979b) studies have been reported recently by Wickens, Mountford and Schreiner (1979). Forty subjects performed four tasks singly and in various pairwise combinations. The tasks, which included tracking, spatial judgment, digit classification and auditory memory, were selected to load different modalities or different stages of the information processing sequence. The obtained patterns of dual-task interference gave no evidence whatsoever for a general time-sharing ability. Time-sharing subcapacities, defined with respect to specific stages of processing, modalities and hemispheres were suggested, however.

It could be argued that the failure to find correlations across dissimilar task combinations in the foregoing studies is due to the fact that subjects use different strategies to meet the concurrent demands of different task combinations. For this account to work, it must be additionally assumed that the effectiveness of the strategy used by a subject is uncorrelated with that of the strategy he or she used with other,

dissimilar, pairings. Thus the results could be due to differences across task pairings in how effectively central capacity is used rather than in the specific subcapacities tapped.[1] While a strategic account of this sort is possible, it is made somewhat implausible by the fact that failures to find correlations in time-sharing performance have in some cases been obtained under conditions allowing the subject little strategic option (e.g., Hawkins, et al., 1979a; 1979b).

3. Time-sharing without interference

Another line of evidence used against the idea of an undifferentiated processing capacity comes from studies showing that two information-processing tasks can be carried out simultaneously without interference. It has been reasoned by some researchers (e.g., Allport, In Press) that if the notion of capacity implies that virtually all tasks draw on a common capacity-limited process or resource, a failure to find performance deficits under dual task conditions constitutes direct evidence against that view. However it is not as simple as that. Advocates of a unitary processing capacity can argue that all such data really demonstrate is that either 1) one or both tasks are "automated" in the sense that they require no attentional involvement or processing capacity or 2) the sum of the demands of the two tasks is simply insufficient to overdrive the undifferentiated central capacity. We will return to these points as we examine some of the findings.

Shiffrin has recently reported a number of studies in which subjects are required either to monitor several channels simultaneously or to monitor only one channel at a time. For example in Shiffrin and Grantham (1973)

subjects were required to monitor visual, auditory and tactile channels either simultaneously (divided attention condition) or sequentially (focused attention condition) for the occurrence of a near-threshold stimulus. Detection performance was found to be no worse under the divided attention condition than under the focused attention condition. This finding seems contrary to the idea of a single capacity that either must be diffused across the three modalities or arbitrarily focused on the correct modality on only one-third the trials under the divided condition. However the results are subject to an alternative analysis. Posner and Klein (1973) have found that neither auditory nor tactile detection requires attention, presumably because of the presence of automatic "alerting" pathways in these modalities. Such pathways do not appear in vision. Therefore it is possible that Shiffrin and Grantham's subjects simply directed attention to the visual modality on divided attention trials, detecting auditory and tactile stimuli by means of alerting pathways. Some support for this view appears in recent work by Hawkins, Shulman and Cohen (unpublished manuscript) who have found that auditory detection requires attention only under conditions in which activity in alerting pathways are depressed or masked by white noise. Also consistent with this analysis are two further sets of findings. The first comes from a study by Shiffrin, Craig and Cohen (1973) in which subjects had to monitor two or three skin sites, either simultaneously or sequentially, for near threshold stimuli. No divided attention deficits were obtained. Similar results were subsequently obtained in the auditory modality by Shiffrin, Pisoni and Castaneda-Mendez (1973). In contrast, Posner (1977; 1978) has found in several studies that visual detection

latency is significantly faster under focused, relative to divided, attention conditions.

In a series of experiments, Shiffrin and Gardner (1972) presented subjects with a rapid succession of visual stimuli with several possible target locations which had to be monitored either simultaneously or successively for the occurrence of a specified target item (a letter). Target detection was about equal under simultaneous and successive conditions. Since monitoring visual channels is known to require processing capacity in some sense (Posner, 1977; 1978), these results seem to provide impressive evidence against an undifferentiated processing capacity. However another analysis is possible. Duncan (In Press) has recently repeated the Shiffrin and Gardner studies, both in their original form and with a slight variation. In the variation, subjects were required to monitor several visual channels to determine whether one _or_ two representations of a target item were present. While subjects had no difficulty looking for a single target item under *divided attention* conditions (as in Shiffrin and Gardner), they had considerable difficulty looking for two targets under these conditions. A reasonable interpretation of these findings is that under the single target condition, subjects do not attempt to split their attention across channels: they direct attention to a particular location in memory (the target code) and respond when this is activated. This tactic apparently won't work under the double-target condition studied by Duncan, however, because activation of the internal target code is presumably insufficient to discern between cases of single and double target presentation.

Along a somewhat different vein, several studies have demonstrated that individuals highly skilled at complex tasks can carry these out with other demanding tasks with little or no cost. An example is provided by the study of skilled keyboard performers by Allport, Antonis and Reynolds (1972). With only modest amounts of time-sharing practice (up to 30 minutes) these subjects were able to play pieces they had not seen before, on sight, while at the same time shadowing tape-recorded English prose presented at a rate of 150 words per minute.

Another example is provided in a study of Japanese abacus operators by Hatano, Miyako and Binks (1977). These subjects, who are highly skilled at mental calculation, were able to perform abacus calculations without apparent cost while at the same time answering general information questions or repeating three-digit numbers. However, if the task paired with abacus calculation itself required arithmetic transformations, even simple ones, severe impairments in performance were observed.

In general, studies of continuous self-paced tasks of the type just described are open to the criticism that highly experienced performers may be able to quickly learn to interleaf the processing demands of the familiar tasks presented to them so that no apparent performance losses can be detected (Moray, 1967). The finding that dual-task interference is similarity-dependent may mean that added track-keeping demands are imposed when the two sets of processes interleaved have common content. Thus, it would appear that evidence of time-sharing without interference does not constitute a convincing argument against the idea of an undifferentiated central capacity.

4. Conclusion: is processing capacity unitary or multi-element?

It is clear from the foregoing review that the issue of unitary versus multi-element processing capacity is not yet fully resolved. However, as noted previously in this report, several sources of evidence suggest that the central processor described in theories of unitary processing capacity might best be viewed as one among several specialized, capacity-limited mechanisms comprising the human information processing system. While this mechanism may be important to efficient performance in many task situations, this would not appear always to be so. In particular, many highly overlearned tasks seem to require relatively little capacity.

While many theoretical questions relating to the exact nature of human mental capacity remain open in the literature we have examined, a clear message emerges regarding the utility of the secondary task approach to workload measurement. Put most simply, the message is that the approach is unworkable. It will not work because the measured workload of a given task is contingent upon the (secondary) task with which it is paired. Consequently, the workload ordering obtained for a given set of primary tasks when these have all been paired in turn with a given secondary task is not apt to be identical to that obtained when another secondary task is used. Consequently no generalizable metric is possible.

C. Fixed capacity

The secondary task approach to workload measurement is based not only on the assumption of an undifferentiated central capacity, but also on the assumption that this capacity is fixed in quantity or proportions. If

capacity is not of fixed, secondary task measurements of workload lose some of their metric qualities. Kahneman (1973) and Welford (1968) have suggested that capacity is in fact elastic, capable of expanding with task demand up to some limiting value. If this were true, then the best one could hope for is an ordinal scaling of mental workload. It might be more complicated than this. Suppose that capacity were a non-monotonic function of workload; that capacity operates according to the Yerkes-Dodson law. The Yerkes-Dodson function relates motivation or arousal level to performance, showing that as these internal states increase in intensity, performance first increases, but beyond some point actually decreases. If we view arousal as the mediating mechanism connecting increased demand to performance, it becomes reasonable to consider the possibility that increases in demand can, under certain conditions, promote the shrinkage of capacity.

As we will see, the evidence regarding the elasticity of capacity, like that reviewed in relation to the assumption of unitary capacity, is highly equivocal. Two approaches have been taken to evaluate the effects of arousal on performance. One of these is to observe the relationship between physiological indications of arousal (e.g., GSR, pupil dilation, heart rate parameters) and performance while manipulating some variable that "ought" to affect arousal level (e.g., incentives, task difficulty, external noise, caffeine, etc.). An example is a study by Kahneman, Peavler and Onuska (1968) in which subjects performed easy and difficult tasks under conditions of high and low monetary incentive. The pupilary response was used as an index of arousal. By this criterion, arousal was greater when subjects performed the difficult relative to easy task, but was unaffected by incentives.

Another more common approach is simply to introduce conditions into the task environment that on theoretical grounds should induce changes in arousal and then observe the effects of these conditions on task performance. A factor that has been studied extensively is acoustic noise, which is believed to increase arousal. A variety of experiments have demonstrated that noise indeed benefits performance. McGrath (1963) for instance found improvements in visual vigilence when the vigilence task was accompanied with moderate intensities (72dB) of noise. Berlyne, Borsa, Hamacher and Koenig (1966) found that 75dB noise bursts, delivered during presentation of certain items, led to improved performance on delayed (but not immediate) recall of the items. The literature showing improvements in performance under noise is thoroughly reviewed by Poulton (1979).

More intense noise bursts, however, have sometimes been shown to reduce performance, just as one might expect on the basis of the Yerkes-Dodson function. Woodhead (1964) administered intense noise bursts while subjects attempted to perform mental arithmetic. If the noise occurred during problem presentation, which was visual, performance impairments were observed. Similar results have been described by S. Fisher in an unpublished study (reported by Broadbent, 1971) of serial reaction time. Response latencies were increased on stimuli presented along with brief noise bursts as low as 80dB in intensity.

Thus there exists some evidence suggesting that capacity may be elastic. Such a conclusion, of course, rests on the view that the manipulations we have described are having their effects through changes in capacity. Another analysis is possible. It could be that the effect of so-called arousing

stimuli is to <u>focus</u> attention. Up to some point, increases in attentional focus (to the exclusion of irrelevant, distracting sources of stimulation) would seem desirable. Over-focusing (to the exclusion of relevant aspects of the task) is not. Evidence consistent with this possibility appears in work by Hockey (1970). Subjects performed under dual-task conditions, either with or without white noise in the background. One of the tasks was tracking, with target and cursor located central relative to the subject's line of gaze. The other task, choice RT, entailed responding to stimuli located more peripherally relative to line of gaze. The results were that while noise improved performance on the central tracking task, it led to declines in performance on the peripheral RT task. This performance did not improve overall with noise: rather attention appeared to be concentrated on the more central task.

While one may question whether or not capacity is expandable, the data and logic we have presented in this section raise genuine difficulties for the secondary task approach to workload measurement. The problem is that for one reason or another--because of capacity changes or focusing--the resources invested in task performance could well be affected by task demand.

V. Summary and conclusions

By and large, the argument against secondary task analyses of mental load or attentional demand have been based on the claimed disconfirmation of certain key theoretical assumptions underlying the analysis. The most crucial of these assumptions is that human information processing is governed by an all-purpose limited-capacity processor. Also important is the related

assumption that the system contains no significant subcapacities that are special to particular modalities, coding systems or processing stages. A third assumption, of lesser importance than the first two, is that capacity is inelastic across levels of task load.

In many cases we have found that the data and arguments pertaining to these assumptions are inconclusive. Of the data presented in support of the existence of structural limitations during the input stage of processing, for instance, only those of Keele (unpublished manuscript) and of Treisman and Davies (1973) seem persuasive. The Keele results are particularly important for they demonstrate both structural interference and structural facilitation. The first of these findings, which occurs when stimuli are relatively complex, implies the presence of structural limitations at some point during the processing of input, and the second suggests the presence of a general-purpose processor which can be directed to a particular modality or modality-related memory location to speed or give priority to processes taking place there (Posner, Personal Communication). For present purposes, the more important implication of these findings is the twofold problem they pose for the secondary-task analysis of workload: both structural interference <u>and</u> structural facilitation lead to situations in which the measured workload of a primary task is dependent upon the modality relationship between that task and the particular secondary task with which it is paired. Either situation will substantially limit the generality of the workload rating obtained.

We have seen that the interpretational problem is even more severe in the case of data put forward in support of structural interference during output processing. The difficulty here is that the relatively poor

performance observed when the same response modality is called on by two concurrent tasks may be due to response competition rather than to structural interference. Thus the data do not argue unequivocally for either modality-specialized subcapacities or a unitary, all-purpose processor. Nevertheless the data do pose a genuine difficulty for the secondary task approach: the workload rating obtained for a given task will be dependent upon the relation between that task's response modality and that of the secondary task. The consequence is as above--potentially severe limitations in the generality of obtained workload ratings.

A similar problem exists with much of the data used to argue for the existence of structural interference at the most central levels of the information-processing sequence. Whereas similar operations, or operations entailing a common coding system, will sometimes show greater mutual interference than those that do not share such commonalities, it is often unclear whether the source of the interference lies in structural limitations on the quantity of information that can be processed or confusions arising between items possessing similar codes or content. However, the data pose a problem for the secondary task analysis regardless of how they are interpreted. The problem is as before: the workload index obtained for any task will vary according to the similarity in code or content of the internal representations generated by that task to those generated by the paired secondary task.

A second source of data used to argue against a unitary processing capacity comes from studies seeking evidence of a general time-sharing ability. The results of these studies are uniform in showing no evidence for a generalized ability to time-share two tasks. However, once again the data are subject to an alternative analysis--one based on the assumption

that subjects use different strategies in meeting the processing demands of different task pairs. If this latter possibility were the case, the time-sharing studies would not pose a major problem for the secondary task analysis of workload. However we do not find the possibility a very plausible one because at least some of the studies reporting no correlations in time-sharing performance across task combinations have studied tasks that admit to little strategic variation (Hawkins, et al., 1979a; 1979b).

A third argument that has been used against unitary processing capacity comes from studies showing that tasks which exhibit little apparent similarity in specific processing demand can be carried out concurrently without interference. The studies have been interpreted as most compatible with a multiple processor view along the lines of that proposed by McLeod (1977) and Allport (In Press). As we have noted, however, these studies can also be interpreted as showing that familiar tasks may impose processing loads that are simply insufficient to produce measurable interference.

Finally, while some evidence has appeared in support of the idea of elastic capacity, the evidence is hardly persuasive. It is important to bear in mind, however, that the evidence _for_ fixed capacity is no more persuasive. Until this issue can be resolved, we have no way to establish to metric qualities of workload scales generated by the secondary task approach, even if the other problems we have described were absent.

Considered altogether, the literature we have reviewed argues rather convincingly against the validity of the secondary task approach to the measurement of mental workload. This is so in spite of the fact that the data remain very much equivocal regarding whether or not processing capacity is unitary in nature and whether or not it is of fixed proportions.

Footnote

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Abstract

In a commonly used sense, mental workload refers to the proportion of an individual's total processing capacity taken up by a particular cognitive task or task combination. One approach to the assessment of mental workload is called the secondary task analysis. In this approach, the operator is required to carry out two simultaneous tasks, assigning one (the primary task) a high priority and the other (the secondary task) a lower priority. The primary task's mental workload is defined in terms of the degradation in secondary task performance occurring under dual- relative to single-task conditions. The validity of this approach critically hinges to the validity of the assumptions a) that human processing capacity is unitary or undifferentiated· b) that the human information processing system contains no significant task-specific capacities; and c) that overall capacity remains invariant across changes in processing demand. The theoretical literature pertaining to these assumptions is reviewed. It is found that while many of the theoretical issues surrounding the assumptions remain unresolved, the available data argue strongly against the general advisability of the secondary task approach. The problem is that the workload ordering obtained by this approach for any set of (primary) tasks can be expected to vary with the secondary task used. Consequently, the approach will not yield a general measue of workload demand.